Thermodynamics and Phase Structure of Strongly-Interacting Matter

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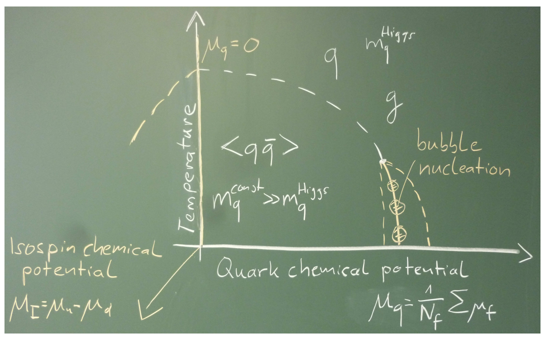
Introduction & Motivation

The characteristic properties of strongly-interacting matter can be described by its **phase diagram** of which a sketch is shown below.

We use an **effective model** to capture the most important properties in form of symmetries using the fundamental degrees of freedom.

→ Dynamical mass generation of constituent quarks by spontaneous **chiral symmetry** breaking.

→ **Centre symmetry** breaking by deconfined, dynamical quarks to describe the deconfinement phenomenon.



Aspects of the phase diagram that we address are

- Temperature dependence of order parameters and thermodynamics at **vanishing density** [1,2].
- **Isospin-density dependence** of the phase structure and thermodynamics [3].
- Surface tension for phase conversion by **bubble nucleation** [4].

Central quantity for our investigations is the thermodynamic potential of the **Polyakov-Quark-Meson model**

$$V_{\rm PQM} = V_{q\bar q}^{\rm vac}(\sigma_f) + V_{q\bar q}^{\rm th}(\sigma_f, \Phi_r, \Phi_i; T, \mu_q, \mu_I, \mu_s) + U(\sigma_u, \sigma_d, \sigma_s) + \mathcal{U}_{\rm glue}(\Phi_r, \Phi_i; T, \mu_q, \mu_I, \mu_s)\ .$$

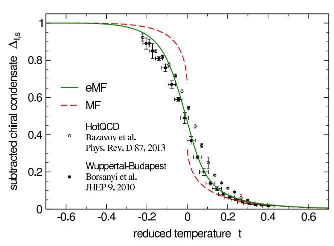
Important modifications that we included are

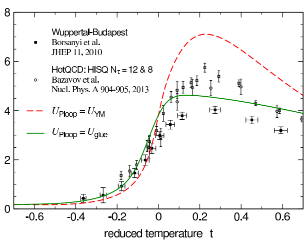
- Generalisation of the mesonic self-interaction potential U to **distinguish chiral symmetry breaking for up and down quarks** [3].
- **Unquenching of the Polyakov-loop potential $\mathcal{U}$ to** consider the **quark-backreaction** onto gluons [1,2].
- **Replacing the Polyakov-loop variables** by their real and imaginary parts **Φ_r and Φ_i** to get a potential whose **solutions are minima** [4].

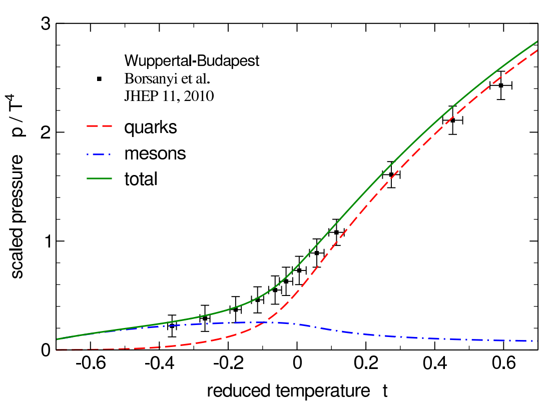
Results: Vanishing density

Our results for order parameters and thermodynamics at vanishing density are **quantitatively consistent with latest lattice data** [1,2].

Here, we show results for the temperature dependence of the subtracted chiral condensate, the interaction measure and the pressure as a function of the reduced temperature $t = (T - T_c)/T_c$.







Crucial ingredients for this agreement proved to be

- Including **quark quantum fluctuations** ($V_{q\bar q}^{\rm vac}$).
- Adding the contribution from **thermal fluctuations of mesons**: $p = -V_{\rm PQM} + p_\pi$.
- Considering **the back-coupling of quarks onto gluons** in the Polyakov-loop potential.

Unquenching the Polyakov-loop potential

Refs. [5,6] calculated the Polyakov-loop potential in **pure gauge theory** and that of **full QCD** with the Functional Renormalisation Group approach.

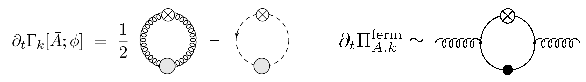
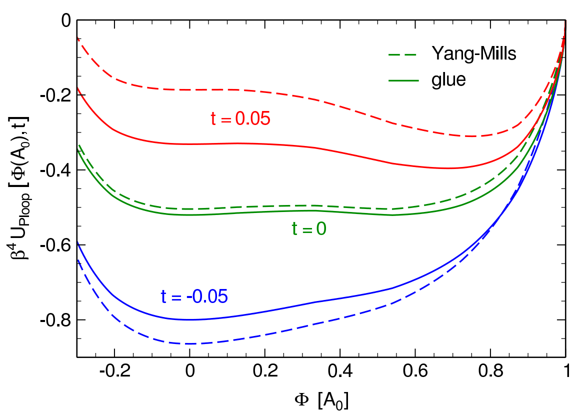


Fig.: Functional flow for the gauge part of the effective action (left). Differences in the glue sector between pure gauge theory and full QCD appear by the quark polarisation contribution to the gluon propagator (right).



Both potentials show a **very similar form** but there is an **offset** between both for non-vanishing reduced temperatures

$$t_{\rm YM} = \left(T - T_{\rm cr}^{\rm YM}\right)/T_{\rm cr}^{\rm YM}\ , \qquad t_{\rm glue} = \left(T - T_{\rm cr}^{\rm glue}\right)/T_{\rm cr}^{\rm glue}$$

⇒ We can describe the **glue potential of QCD** with existing parametrisations of the **pure gauge potential** by evaluating these at a **different reduced temperature** [1].

$$\frac{\mathcal{U}_{\rm glue}}{T^4}(\Phi_r, \Phi_i; t_{\rm glue}) = \frac{\mathcal{U}_{\rm YM}}{T_{\rm YM}^4}(\Phi_r, \Phi_i; t_{\rm YM}) \quad \text{with} \quad t_{\rm YM} = 0.57\, t_{\rm glue}$$

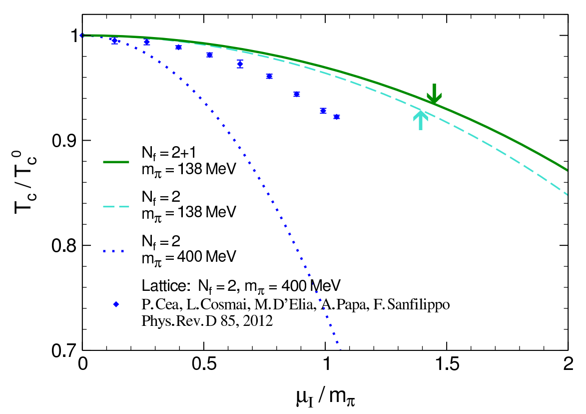
Test: Non-vanishing Isospin

- An **imbalance of protons and neutrons** is present in **nature**: heavy ion collisions, compact stars, supernovae, early universe.

With the correct description of the temperature dependence at vanishing density we want to **test our framework at non-zero isospin density**.

→ We make predictions for the **isospin dependence of thermodynamics and order parameters** [3].

→ We compare with the best lattice data (two flavour, $m_\pi = 400$ MeV) for the **isospin dependence of the pseudocritical temperature** and make predictions for $2+1$ flavours and physical particle masses.



→ We find a **larger curvature** than seen on the lattice. A similar failure is observed for the magnetic field dependence [7].

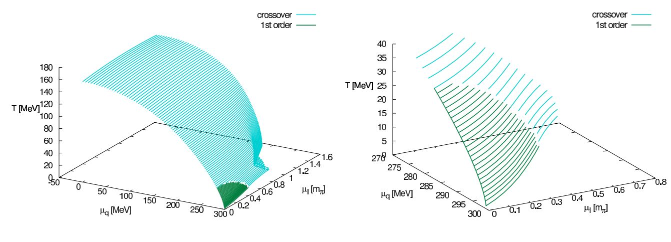


Fig.: Phase diagram, three dimensional in temperature, quark and isospin chemical potential space (left) and zoom to the first-order region (right). From Ref. [3].

→ With increasing isospin chemical potential the **first-order region shrinks**.

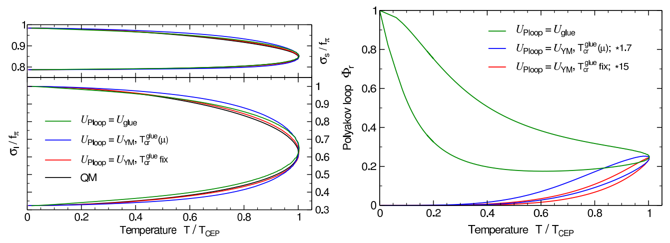
→ For an analysis of the **pion condensation phase** in the two flavour Quark-Meson model, see Ref. [8].

Phase Conversion: Bubble Nucleation

- The phase conversion in a **first-order phase transition** close to the coexistence line is driven by bubble nucleation.
- The **nucleation rate** of such bubbles in the thin-wall approximation depends on the **surface tension**: $\Gamma \sim e^{-\Sigma^3}$.
- On the **coexistence line** the surface tension is related to the potential in the **straight line approximation** via [4]

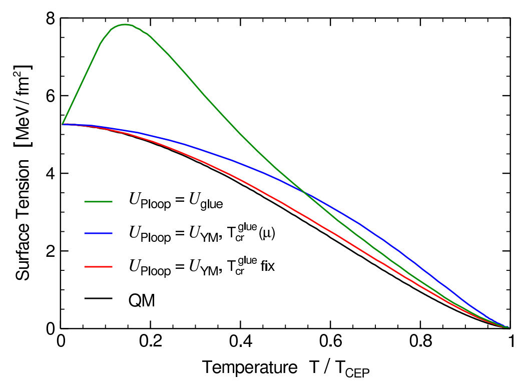
$$\Sigma(T,\mu_f) = h \int_0^1 \mathrm{d}\xi \sqrt{2\, V_{\rm PQM}(\xi; T, \mu_f)}\ , \qquad \text{with}$$

$$h^2 = \frac{1}{2}(\Delta\sigma_u)^2 + \frac{1}{2}(\Delta\sigma_d)^2 + (\Delta\sigma_s)^2 + (2\kappa\Delta\Phi_r)^2 - (2\kappa\Delta\Phi_i)^2\ .$$



→ We find **moderate values** for the surface tension.

→ The timescale for bubble nucleation is smaller than the dynamical timescale allowing for a **quick phase conversion** in heavy ion collisions, supernovae and the early universe.



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